Keeping COMMx COOL

NRL Addresses a Hot TacSat-4 Challenge

Before the U.S. Navy's TacSat-4 satellite could provide crucial **communications, data exfiltration, and tracking functions, difficult thermal control** requirements for the onboard electronics had to be met. Using traditional methods of spacecraft thermal design, project **engineers could not find adequate heat** rejection space in the satellite design for its COMMx electronic payload without making the satellite too large and heavy. NRL researchers stepped in and were able to apply their Central Thermal Bus concept developed in the 1990s to redesign the thermal payload control system for the **most efficiency in terms of performance,** ease of integration, and, most importantly, mass/volume, without limiting payload performance or mission goals.

Design and Analysis of the Thermal Control System for the TacSat-4 Spacecraft COMMx Payload

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The thermal requirements for the TacSat-4 payload electronics (COMMx) were difficult to meet with traditional methods of spacecraft thermal design. TacSat-4 is a U.S. Navy satellite intended to be launched into an elliptical orbit to provide relevant capabilities for communications, data exfiltration, and tracking. In a conventional passive thermal design, the electronics boxes are distributed around the spacecraft at suitable locations where heat rejection to space is available. This technique, while simple, can be inefficient with satellite real estate and so posed a real threat to COMMx payload implementation. Specifically, the spacecraft would become large and heavy due to inefficient packaging, requiring a larger and more expensive launch vehicle. The result of a trade study indicated that a Central Thermal Bus design, a concept first proposed by the U.S. Naval Research Laboratory in 1994 and the subject of a funded study in 1999, would yield the most efficient thermal control system for the TacSat-4 payload in terms of performance, ease of integration, and more importantly, mass/volume. The challenge facing NRL thermal engineers was to design the payload thermal control system to fit within the multitude of program constraints without limiting payload performance or mission goals.

INTRODUCTION

TacSat-4 is a Navy-led space program jointly sponsored by the Office of Naval Research (ONR), Office of the Secretary of Defense (OSD), and Department of Defense Operationally Responsive Space (ORS) Program Office to provide relevant capabilities for communications, data exfiltration, and tracking. Figure 1 illustrates the basic configuration of the TacSat-4 spacecraft. The satellite, comprising a separately developed bus and payload, will be launched into a 4-hour elliptical orbit, shown in Fig. 2, to provide maximum operation time over the geographical areas of interest. A 12-foot deployable ultra-high frequency (UHF) antenna and associated electronics payload are designated COMMx, with the electronics boxes housed inside a relatively small enclosure.

The challenges facing the COMMx Thermal Control System (TCS) were extensive. Extreme heat dissipation given the small size of the payload, some 600 W, while coping with significant periods of payload off-time made management of component temperatures difficult. The temperature limits of the electronics boxes are 0 °C to +40 °C during normal operations and –30 °C to +50 °C during the survival mode. Variable spacecraft orientation meant that the radiator sink could change from deep space to full Sun during payload operations. To prevent "back-loading" of absorbed solar heat to the payload, thermal diode (action) devices were required in the TCS design. Additionally, traditional limitations associated with a Class D space program, including high risk and limited funds, along with constraints on power, mass, and volume, converged to force a novel TCS architecture solution.

At the beginning of the development program, a trade study of various technologies and architectures was carried out. The result indicated that only one solution met the aforementioned requirements. It entailed the Central Thermal Bus (CTB) concept and the Loop Heat Pipe (LHP) technology in conjunction with an LHP temperature control method. The CTB architecture for a spacecraft TCS was first proposed by the Naval Center for Space Technology (NCST) at the U.S. Naval Research Laboratory (NRL) in 1994. It then became the subject of a funded experimental study in 1999.[1] The essence of the CTB approach is to package all heat-dissipating devices close together at a central location inside the spacecraft while using a cooling technology to (a) collect the waste heat, (b) transport it to the spacecraft radiators, and (c) reject it to space at a place where the heat removal is the most efficient (i.e., the coldest sink). The CTB offered many advantages over traditional TCS architectures. Among them are mass/volume savings of the TCS, ease of integration of the payloads, and optimal placement of the electronics inside the spacecraft to enhance radiation shielding. As presented below, the LHP technology played a crucial role in providing the heat transport for the CTB. Like conventional heat pipes, LHPs are two-phase heat

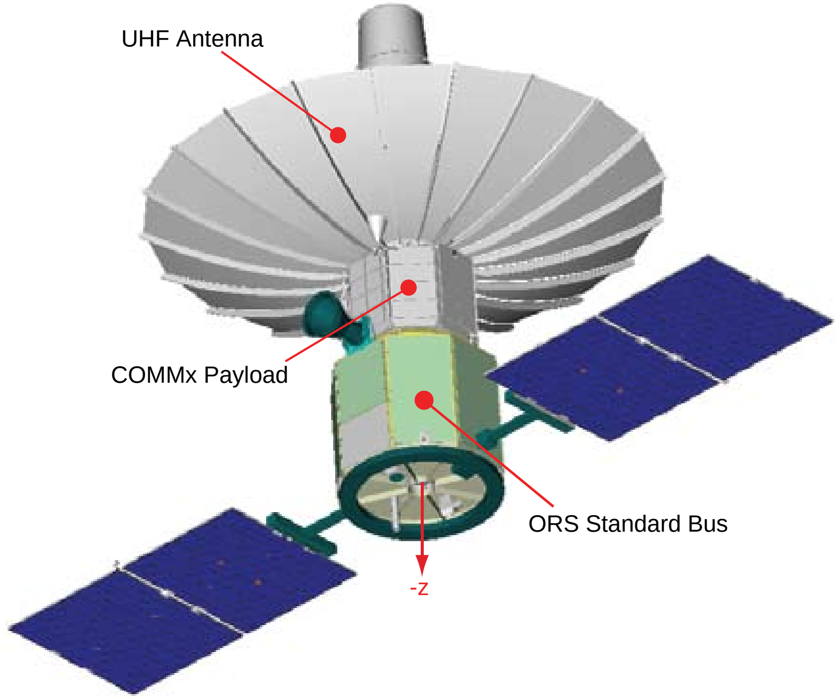

FIGURE 1
TacSat-4 spacecraft with deployed UHF antenna.

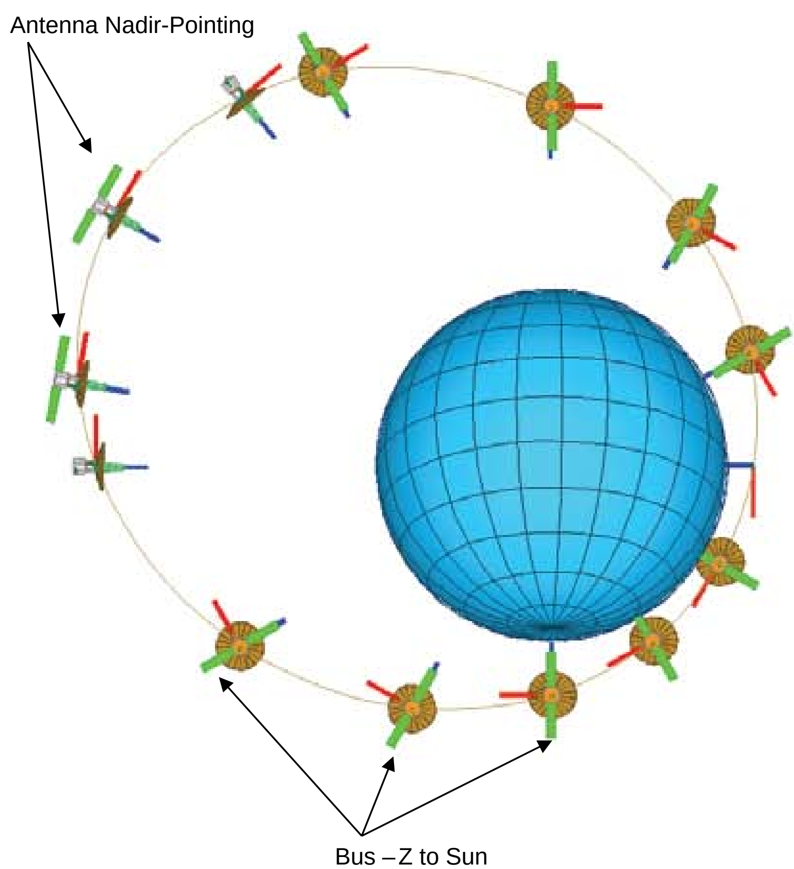

FIGURE 2
TacSat-4 elliptical orbit at a high beta angle, as viewed from the Sun.

transport mechanisms using only capillary action to circulate the working fluid in a closed loop. LHPs have no mechanical moving parts to wear out or require lubrication, resulting in tremendous operational reliability and long service life.

TACSAT-4 MISSION

The TacSat-4 mission provides operationally relevant capabilities and advancements in Operationally Responsive Space (ORS). The TacSat-4 payload (COMMx) consists of 10 UHF channels that will be used in any combination of communications, data exfiltration, or Blue Force tracking. The mission enables communications-on-the-move with legacy radios and provides a wideband Mobile User Objective System "MUOS-like" channel. The 4-hour elliptical orbit provides 1- to 2-hour dwells per pass that augment the geosynchronous communications by facilitating a near-global (but not continuous) coverage, including high latitudes. The TacSat-4 program advances key ORS interests such as spacecraft bus standards, long dwell orbits, dynamic tasking, and net-centric operations.

OVERVIEW OF THERMAL TECHNOLOGY

Fluid circulation in a closed loop is an effective way to transfer heat from one location (e.g., payload electronics) to another (e.g., space radiators). For space applications, in which high system reliability and long life are often required, the capillary pumped heat transport technologies such as Capillary Pumped Loop (CPL) and LHP are preferred for the TCS. In contrast to mechanically pumped systems, CPLs and LHPs contain no mechanical moving parts to wear out or break down. More importantly, they do not require internal lubrication that can contaminate the working fluid and lead to the generation of non-condensable gas.

The CPL and LHP were developed independently in the United States and in the former Soviet Union, respectively, in the 1980s. Recognizing the need for high-performance thermal management technologies for the Navy's next-generation spacecraft, NRL has been participating in the research and development of advanced two-phase heat transfer technology since 1992. NRL led a joint effort that began in 1996 to demonstrate the CPL multiple-evaporator operation in micro-gravity, culminating with the flight experiment CAPL-3 in 1999.[2] NRL was also a full participant in the flight experiment LHP-FX in 1998.[3] Even though CPL and LHP share many common characteristics, LHP is better suited for COMMx due to its higher heat transport capacity and transient environment tolerance.

Loop Heat Pipe

Figure 3(a) is a functional schematic of the LHP. The LHP consists of a capillary pump, condensers (for simplicity, Fig. 3(a) shows only one condenser), a reservoir (a.k.a. compensation chamber), vapor/liquid transport lines, and a thermoelectric cooler (TEC). An LHP operates as follows: (a) heat from the heat source conducts through the capillary pump casing to vaporize liquid on the outer surface of the wick, (b) the vapor travels along the vapor line to the condenser, where it rejects the heat to revert back to liquid, and finally (c) the liquid flows in the liquid line to the pump to complete the cycle. The LHP condenser is not used entirely for condensation. A portion of it needs to cool the exiting liquid below the saturation temperature that allows the system to overcome the environmental heating and heat leak from the evaporator. Note that there always exists both liquid and vapor (two-phase) in the reservoir such that its temperature and pressure control the saturation condition of the entire loop (i.e., changing the reservoir temperature will result in a corresponding change in the payload temperatures). A detailed description of the LHP and its applications can be found in Ref. 4.

Thermoelectric Cooler

A TEC is a small solid-state heat pump capable of removing 1 to 25 W and providing the heat source a maximum temperature lift of 60 °C. By applying a positive voltage across the TEC, heat is pumped from the cold side to the hot side of the TEC (refrigeration mode). If the voltage polarity is reversed, the heat flow changes direction, resulting in the heat pump mode. Increasing/decreasing the voltage will increase/decrease the amount of heat flow.[5]

Figure 3(a) illustrates the use of a TEC to regulate the heat flow in/out of the LHP reservoir. One side of the TEC is thermally strapped to the reservoir and the other side is strapped to the active portion of the capillary pump body. By regulating the TEC applied voltage, the LHP temperature can be maintained within ± 0.5 °C, keeping the payload at a desired temperature regardless of the operating conditions.

COMMx THERMAL DESIGN

Figure 3(b) presents the functional schematic of the COMMx TCS, and Figs. 4(a) through 4(c) illustrate the actual layout of the components. As seen in Fig. 4(a), the electronics boxes with the highest heat dissipation are mounted on both sides of the main deck. The remaining boxes, selected because of their relatively

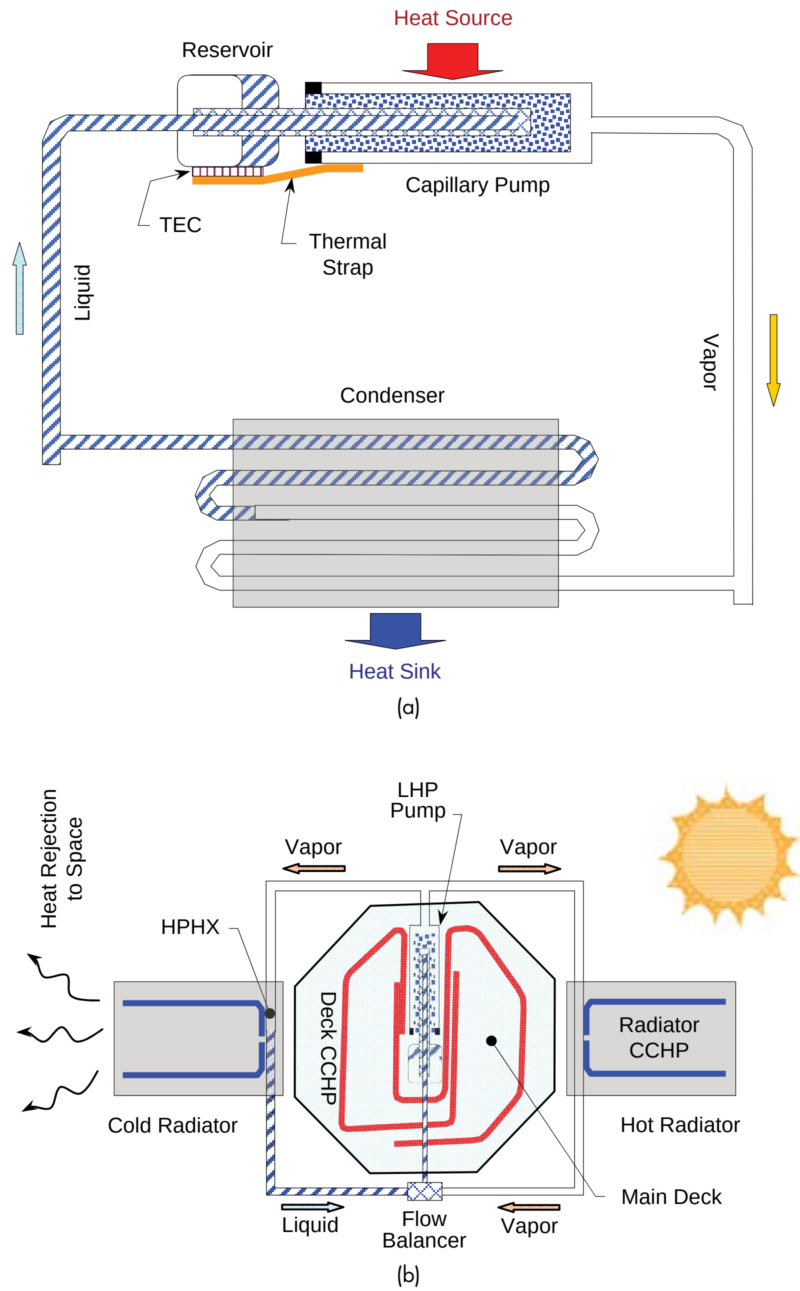

FIGURE 3
(a) Functional schematic of a loop heat pipe with a thermoelectric cooler. (b) Functional schematic of the Central Thermal Bus thermal control system implementation for COMMx.

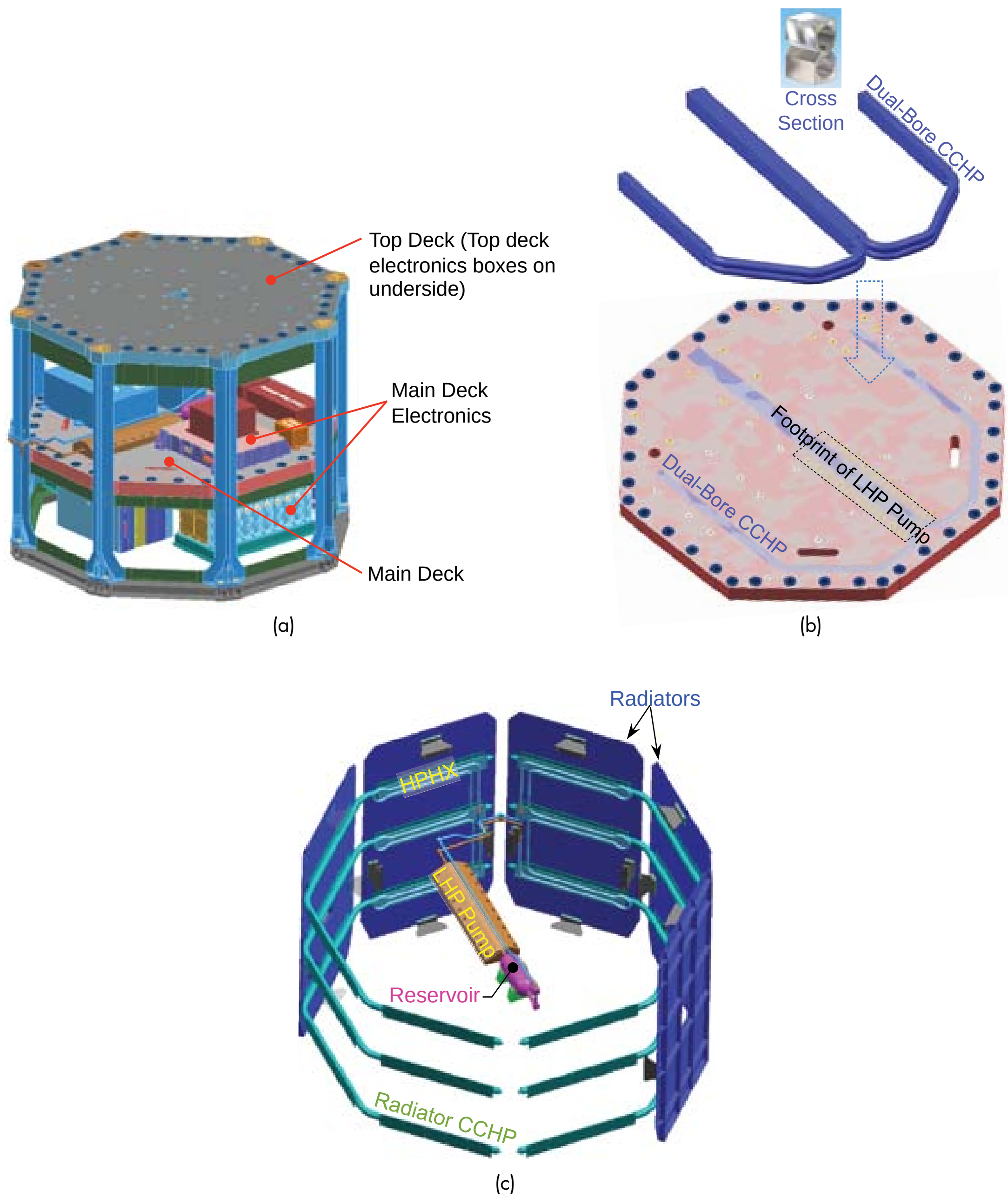

FIGURE 4
(a) Configuration of the COMMx electronics enclosure. (b) Four conjoined CCHPs embedded within the COMMx main deck. (c) Physical configuration of the COMMx TCS including the LHP and radiator CCHPs.

small dissipations, are bolted to the underside of the top deck. The COMMx enclosure is well insulated from the surrounding environment, making the LHP cooling system the sole heat path to the space sink. The cooling system picks up the waste heat from the main deck and transports it to eight radiator panels for rejection. The radiators are supported by, but thermally isolated from, the COMMx structure. Moreover, all interior surfaces of the COMMx enclosure, including the electronics, are provided with a high-emittance surface finish to facilitate radiative heat transfer from the top deck to the main deck where heat transport to the radiators takes place.

The main deck consists of a 1½-in.-thick honeycomb panel embedded with a pair of "dual-bore" constant conductance heat pipes (CCHPs), as shown in Fig. 4(b). The CCHPs efficiently collect the waste heat from the electronics boxes (including those on the top deck via radiation) and deliver it to the LHP evaporator. Since the Sun can illuminate any one side of the payload during the orbit, the eight radiator panels are provided in two separate, thermally coupled groups of four (see Fig. 4(c)). Both sets of radiators are sized to reject the entire heat load in the worst hot case (while one of the two sets faces the Sun). The LHP serves as the variable heat transport system between the deck and the two independent sets of radiators for removal.

Even though the design includes thermostatically controlled heaters to prevent the radiator temperatures from dropping below the ammonia freezing point (–77 °C) in the worst cold case, a decision was made to incorporate heat-pipe-heat-exchangers (HPHX) in the TCS. The HPHX, a 180-in.-long, S-shaped CCHP (see Fig. 4(c)), is the method by which each set of radiators is thermally coupled together. The thermal footprint between the radiator CCHPs and the LHP condensers is sufficiently small to allow the survival heaters to keep the ammonia in the LHP from freezing (even if the radiators are well below –77 °C). Note that CCHPs are freeze tolerant.[6] Finally, the LHP employs a capillary flow balancer to serve as a thermal diode to prevent heat flow from the "hot" radiators (e.g., the radiators illuminated by the Sun) back to the payload (see Ref. 4 for details on the capillary flow balancer).

To ensure that the LHP starts up successfully under any initial system condition, two 25-W "starter" heaters having a ½-in.^{2} surface area are attached to the capillary pump body (see Fig. 5). If the pump fails to start on its own, the starter heater will be activated by the onboard computer to facilitate the (nucleate) boiling process in the pump.[7] A 10-W Kapton film heater is bonded to the reservoir outer surface to serve two functions: (a) to raise the loop temperature for the payload temperature control operation, and (b) to shut down the loop when the payload becomes too cold. In addition, a Marlow TEC Model No. DT3-6 is used to thermally couple the reservoir to the capillary pump (see Fig. 5). The TEC is placed on the pump body with the hot side down. One end of the 6-in.-long by 1-in.-wide by ¼-in.-tall copper bar is secured to the top of the TEC, and the other end to the reservoir. In this application, the TEC functions only as a cooler allowing the loop to lower its temperature for payload temperature control.

To keep the electronics above the temperature limit in the worst cold case survival mode, additional film heaters with a combined power of 44 W are placed at various locations on the top deck (inner surface) and main deck. Likewise, two 40-W line heaters are strung along the LHP condenser lines and a 6-W survival heater is attached to the LHP reservoir to ensure shutdown. The survival heaters are sized with respect to the minimum bus voltage of 22 V.

Figure 6 shows the fully configured payload with the integrated TCS.

TACSAT-4 THERMAL MODEL

A detailed thermal analysis was carried out for the COMMx TCS to predict the on-orbit performance of the cooling system in accordance with the anticipated operating scenarios. A highly complex model of the payload and the cooling system was developed for this purpose. Specifically, the orbital simulations were intended to (a) determine the maximum operation time per orbit, (b) verify that the electronics temperatures meet the limits of 0 °C to +40 °C for normal operation and –30 °C to +55 °C in the survival mode, (c) size the survival heaters, (d) verify that all aspects of the LHP and CCHP operation are nominal (e.g., the wicks do not exceed their respective capillary limits, or the capillary flow balancer provides adequate diode

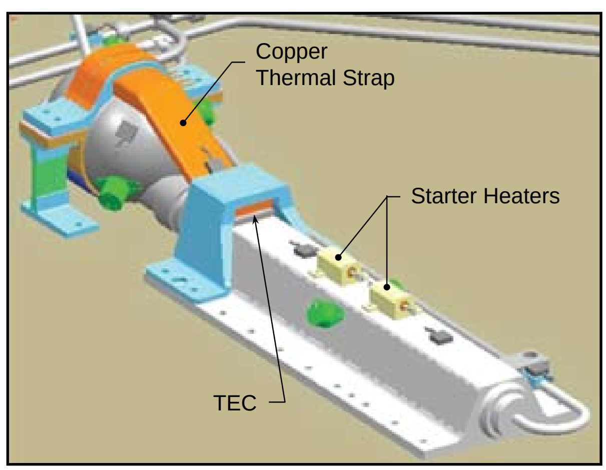

FIGURE 5
COMMx LHP pump-reservoir assembly.

FIGURE 6
Photograph of the fully configured COMMx payload with the integrated TCS.

action in the worst flow imbalance situation), and (e) ensure that the ammonia in the LHP condensers does not freeze in the worst cold case condition given the predicted amount of survival heater power.

Thermal Model Description

The TacSat-4 thermal model was developed with Thermal Desktop (TD) software. TD combines the user-defined Geometry Math Model (GMM) and Thermal Math Model (TMM) into a single platform. A Monte Carlo ray tracing method is used to calculate the radiative couplings (RADKs) for the GMM, while a SINDA-based solver is used to solve the TMM for the nodal temperatures. In addition, NRL incorporates an LHP transient code, developed by TTH Research and refined at NRL, into the subroutine library to advance the LHP temperatures for each time step in the TMM.[8]

As shown in Figs. 7(a) and 7(b), the spacecraft model consists of four major components: the UHF antenna, the COMMx payload, a simplified model representing the ORS Standard Bus and its solar arrays, and the LHP/CCHP cooling system. The TMM contains approximately 10,000 nodes. While SINDA has been the industry standard for spacecraft thermal analysis for the last 30 years, the LHP transient code is a recent development. In 2001, NASA Goddard Space Flight Center funded TTH Research to produce an efficient computer code to be used with SINDA that was capable of solving the transient behavior of LHPs. Following a period of verification processes, NASA and NRL engineers started using the computer code in 2004 for both ground- and space-based LHP systems.[9,10] In short, the LHP code simultaneously solves the equations governing the conservation laws of mass, momentum, and energy for fluid- and thermodynamics.

Model Results

Figure 8(a) presents the results of the maximum power simulation in the worst hot case. As predicted, the COMMx payload can operate for 2 hours per orbit at 600 W of power dissipation. At the end of the 2-hour dwell, the warmest electronics box is roughly 35 °C at the base plate. The boxes on the main deck are nearly isothermal due to the embedded CCHPs.

Figure 8(b) gives the results of the cold survival case electronics box temperatures. During the worst cold case orbit, with no operations and survival heater power only, the thermal model predicts that the electronics boxes remain above their survival temperature limits for both a stowed and deployed UHF antenna.

CONCLUSION

The maturity of the Loop Heat Pipe technology in the United States has enabled the Central Thermal Bus architecture to become a viable thermal control option for spacecraft. In the case of COMMx, the CTB design allows many more heat-intensive electronics to be packaged in a limited volume of the spacecraft than can be achieved otherwise. As a result, the TacSat-4 payload provides exceptional capability in its mission orbital arena. From a broader perspective, success of the space demonstration of the CTB architecture will certainly convince the next generation of spacecraft developers that an "increase in payload capability" does not necessarily equate to "increase the size of the spacecraft." If the satellite volume can be kept small, the more tangible advantage of CTB is perhaps that a mission will not require a larger fairing, or more importantly, a bigger and much more expensive (mission-prohibitive) launch vehicle. Based on these observations, the CTB concept is poised to enable significant improvements in Navy and U.S. space capability.

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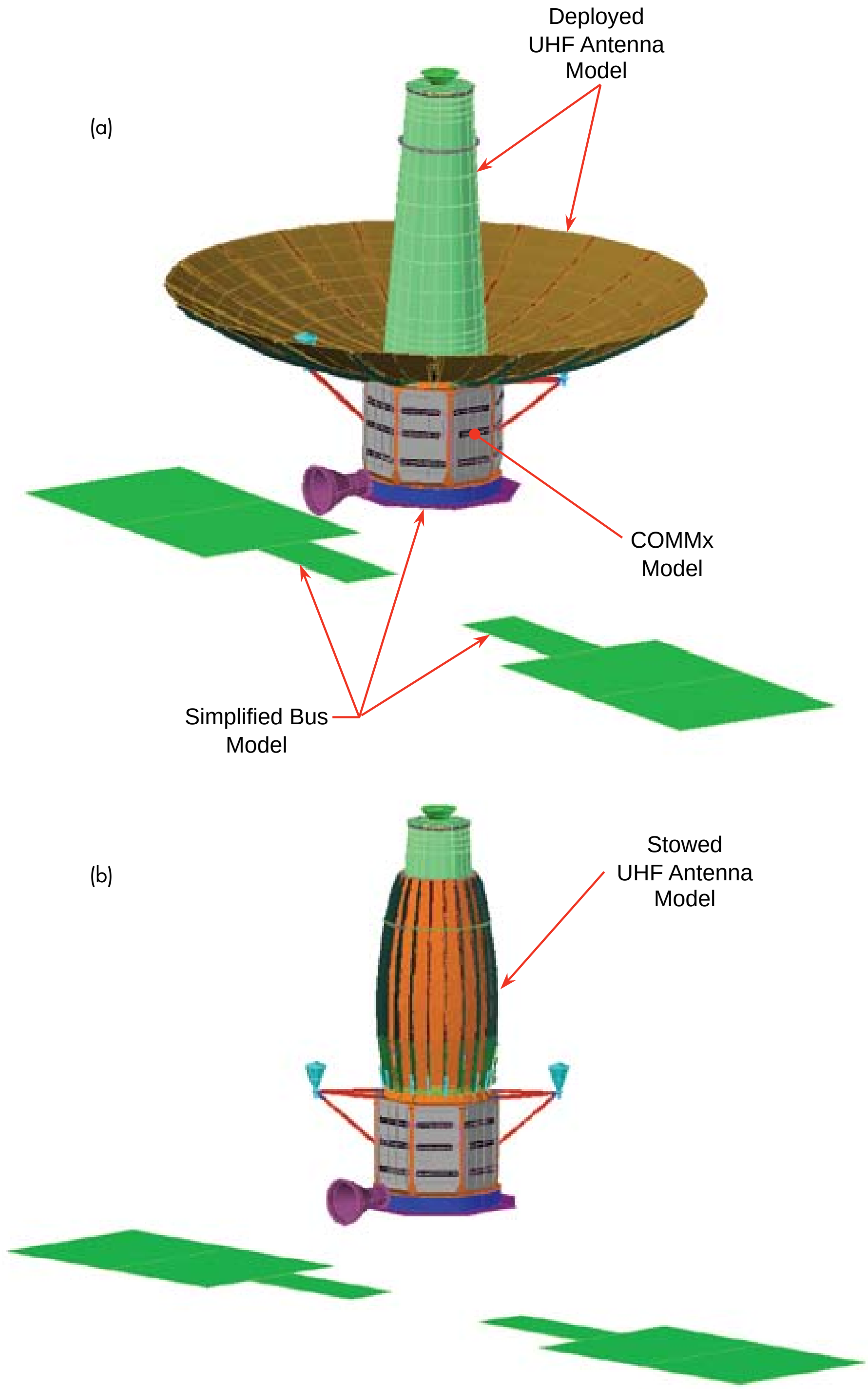

FIGURE 7
(a) COMMx thermal model with deployed UHF antenna. (b) COMMx thermal model with stowed UHF antenna.

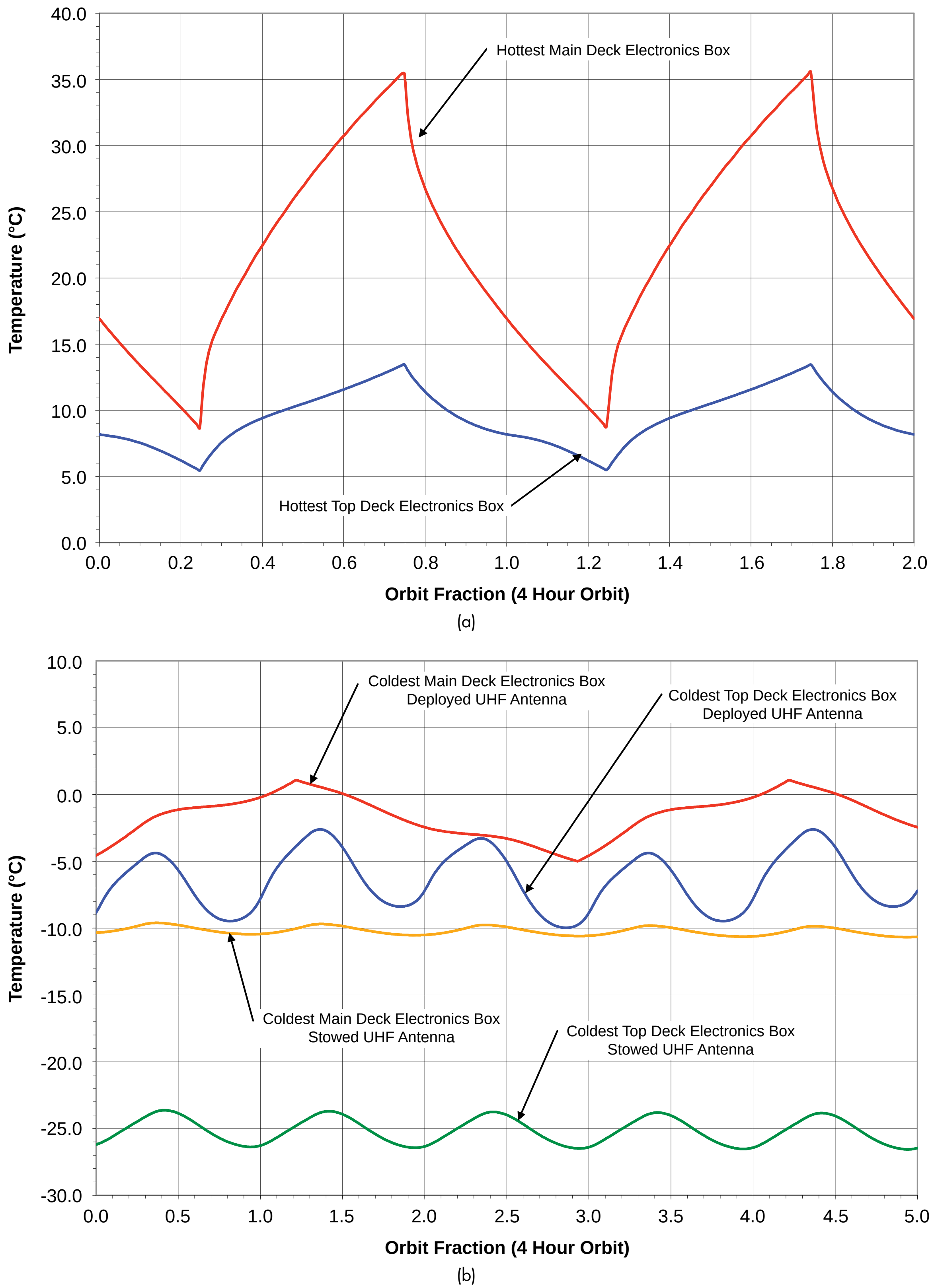

FIGURE 8
(a) COMMx electronics box worst-case temperature predictions for 2 hours of operation per orbit. (b) COMMx electronics box survival temperature predictions.

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